

CHAPTER 3 -- SEQUESTRATION OF CARBON DIOXIDE FROM POWER PLANT EMISSIONS

There are a number of existing technologies, including chemical absorption, adsorption, cryogenic processes, and membranes, that can separate carbon dioxide (CO₂) from the flue gases emitted during power plant operation. The carbon dioxide captured by such processes can then be sequestered by storing it in various underground storage media, including the ocean, aquifers, and depleted oil and gas wells. Another possibility is to put the CO₂ to some type of use, such as perhaps pumping it into the ground to create pressures that enhance oil well recovery.

In the United States, about 463 million metric tons of carbon (MMTC) are emitted from power plants each year. Typically, carbon “scrubbing” technologies have been found to capture about 75-90% of power plant CO₂ emissions (Table 3.1). Therefore, if we assume capture technology was applied to all power plants in the United States, approximately 347 to 417 MMTC could be captured. This amount would equal about 25-30% of total U.S. carbon emissions per year. It must be noted that application of technological means of carbon separation to all U.S. power plants is optimistic, but it does provide some idea of the potential amount of CO₂ that can be captured in the United States each year. This potential appears relatively large; approximately 60-72% of the annual emissions reductions needed to meet Kyoto obligations (Table 3.1).

Technological sinks are an appealing means of sequestering carbon because they may be geographically flexible. Since climate change is a global problem, a recovered ton of CO₂ is equivalent in any location. This principle guides the development of joint implementation (JI). While potential JI projects such as afforestation face many uncertainties concerning the baseline, leakages, and property rights security issues, CO₂ capture technology can be readily installed on developing countries’ power plants. Countries like China and India will likely be the greatest emitters in the 21st century and will probably use their expansive coal reserves to continue developing their economies (DOE, 1997). Consequently, progress in CO₂ capture and storage technology, which could allow this development to occur while simultaneously reducing emissions, could prove extremely beneficial.

While substantial capture potential and practical benefits exist, a major obstacle to implementation is cost. Due to the additional energy needed to capture the CO₂, the application of capture technologies reduces overall efficiency of power generation, thereby increasing costs. This effect is known as the “energy penalty.” Currently, the cost of CO₂ capture is high, with estimates ranging from around \$60-\$250/ton of carbon avoided. When compared to the costs of other mitigation strategies, technological sinks appear relatively expensive. However, research in this area is still in its infancy; further research will likely provide substantial reductions in cost.

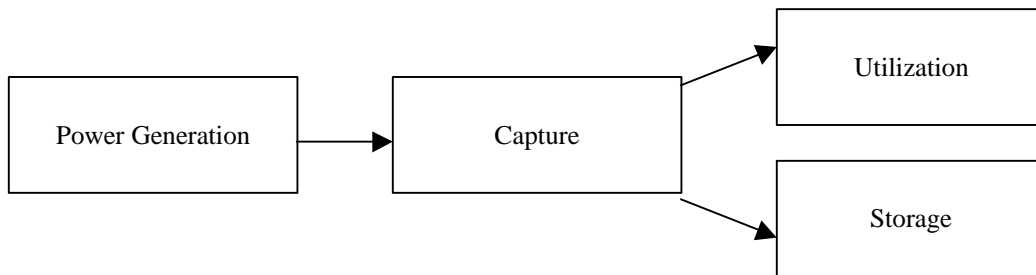
As a mitigation strategy, technological sinks offer the advantage of allowing the continued use of the well-established fossil fuel infrastructure. As the U.S. Department of Energy (DOE) has recently stated, sequestration may be essential for the continued large-scale use of fossil fuels (DOE, 1999). According to the Energy Information Administration, about \$500 billion is spent annually on total U.S. energy. Further, the capital stock of the worldwide utility industry is about two trillion dollars (DOE, 1997). With this tremendous amount of resources invested in our energy-producing sector, it seems logical to invest in developing technology such as CO₂ capture and storage that can

both allow fossil fuels to remain a principal source of power production while acting to minimize emissions of carbon dioxide.

I. Types of “Technological “ Sinks

“Technological” sinks (as opposed to plant “biological” sinks) involve the capture of CO₂ from the power generation process. After the fossil fuel has been burnt to produce power, the carbon dioxide is separated from the flue gas stream or captured. The CO₂ can then be stored or used. The main steps in this process for a standard fossil-fuel power plant are shown below in Figure 3.1.

Figure 3.1 The Technological Sink Process



Several technologies have been developed that can capture about 75 to 90 percent of the emitted CO₂. These capture technologies are described below:

Chemical absorption -- Currently, all commercial power plants that capture CO₂ use processes based on chemical absorption with a solvent. In these processes, a solvent, such as monoethanolamine (MEA), is used in a scrubbing system to remove the CO₂ from the flue gas stream (IEA, 1993).

Adsorption -- Adsorption methods involve a physical attraction between the gas and active sites on the solid. This process contrasts with absorption, which causes a chemical reaction to capture CO₂. These methods are used commercially in process industries and may be applicable to power plants in the future. However, adsorption is currently unattractive because of its high cost and limited capacity (IEA, 1993).

Cryogenic processes -- Cryogenic systems are low-temperature processes which separate the CO₂ directly or through a solvent. CO₂ can be physically separated from other gases by condensing it at low or cryogenic temperatures. Cryogenic processes produce liquid CO₂, which is immediately ready for transport to the disposal site. However, these methods are only considered for Integrated Gasification Combustion Cycle plants, which are not used commercially (IEA, 1993).

Membranes -- This technology involves a membrane which selects and removes certain components from a gas stream because of an absorption liquid on one side of the membrane. This approach is limited by the size of existing membrane separators, but does have the advantage of very

high selectivity. Membranes are used commercially in hydrogen separation, but they would need more development before they could be used on a large enough scale for their costs to decrease (IEA, 1993).

Different capture technologies are appropriate for different power generation types. Even though the energy penalty is high, chemical scrubbing with solvents such as MEA is the most attractive capture option when the CO₂ concentration in the flue stream is low, as in the pulverized coal (PC) and natural gas combined cycle (NGCC) types (Riemer et al, 1995). However, when CO₂ concentrations in the flue gas are higher, as in integrated gasification combined cycle (IGCC), a physical solvent like Selexol is favorable. Adsorption, which involves gas-solid attraction, is only practical with extremely low CO₂ concentrations (1.5% of flue gas). Yet even with low CO₂ concentrations, adsorption still proves more expensive than MEA. Cryogenic processes are only possible with high CO₂ concentrations and prove even more expensive than Selexol. Membranes have potential because they offer lower energy penalties, but the giant size and associated high costs to outfit a large plant are drawbacks compared to the other capture technologies (Riemer et al, 1995).

II. Costs of CO₂ Capture

The major deterrent to these technologies is cost, which increases when the overall efficiency of power generation is reduced as a result of the application of capture technology. This reduced plant efficiency results from the large amount of additional energy needed to capture the CO₂. Typical energy penalties associated with CO₂ capture are illustrated below in Table 3.1. The energy penalties are estimated for both current technology and likely improvements in the next two decades. As shown below, gas typically has a lower energy penalty from capture than coal because gas is less carbon intensive (DOE, 1997). The advanced coal, or IGCC plants, have a relatively low energy penalty because their power production process allows the use of physical absorbents like Selexol.

Table 3.1. Typical Energy Penalties from CO₂ Capture

| Power Plant Type | Today | Future |
|-------------------------|--------------------------------------|----------------------------------|
| Conventional Coal (PC) | 27 - 37% (Herzog and Drake, 1993) | 15% (Mimura et al, 1997) |
| Gas (NGCC) | 15 - 24% (Herzog and Drake, 1993) | 10 - 11% (Mimura et al, 1997) |
| Advanced Coal (IGCC) | 13 - 17% (Herzog and Drake, 1993) | 9% (Herzog and Drake, 1993) |

Herzog (1998) conducted a comparison of published studies from the past several years that analyzed the costs of capturing CO₂ from flue gas of various power generation plants (see Table 3.2). The studies were separated into three categories according to power generation type: capture from pulverized coal (PC), capture from Integrated Gasification Combined Cycle (IGCC), and capture from Natural Gas Combined Cycle (NGCC) power plants. All PC and NGCC studies were based on MEA scrubbing, while IGCC plants used scrubbing practices involving physical absorption. All the

Table 3.2 Cost of Capture Among Various Power Generation Types

| Study | Argonne | EPRI | Utrecht | IEA GHG | Essen | EPRI | Utrecht | Fluor | IEA GHG | Trondhei m |
|--|---------|------------|----------|---------|-----------|---------|---------------|---------|---------|---------------|
| Reference | Doctor | Condorelli | Hendriks | Audus | Prusc hek | Smelser | Hendrick s | Mariz | Audus | Bolland |
| Plant Type | 1996 | 1991 | 1994 | 1995 | 1996 | 1991 | 1994 | 1995 | 1995 | 1992 |
| CO ₂ Emitted without capture (kg/kWH) | 0.8 | 0.87 | 0.8 | 0.78 | 0.69 | 0.91 | 0.8 | 0.91 | 0.41 | 0.4 |
| CO ₂ Emitted with capture (kg/kWH) | 0.2 | 0.1 | 0.1 | 0.17 | 0.09 | 0.14 | 0.1 | 0.14 | 0.075 | 0.046 |
| % Reduction in CO ₂ Emissions | 75 | 88 | 88 | 78 | 87 | 85 | 88 | 85 | 82 | 89 |
| Plant Efficiency without capture (HHV) | 36.6% | 35.4% | 43.6% | 39.9% | 45.0% | 34.8% | 41.0% | 34.8% | 50.0% | 47.4% |
| Plant Efficiency with capture (HHV) | 33.2% | 28.5% | 36.3% | 34.0% | 34.7% | 22.9% | 31.5% | 24.0% | 41.0% | 40.4% |
| Energy Penalty | 9.0% | 19.0% | 17.0% | 15.0% | 23.0% | 34.0% | 23.0% | 31.0% | 18.0% | 15.0% |
| Cost Basis | 1995\$ | 1990\$ | 1990\$ | 1993\$ | 199? \$ | 1990\$ | 1990\$ | 199? \$ | 1993\$ | 1992\$ |
| Effective Capital Charge Rate | 11.1% | 12.8% | 7.1% | 9.4% | ? | 10.1% | 7.1% | 12.3% | 10.5% | 8.6% |
| Electricity price without capture (cents/kWH) | 5.8 | 5.7 | 3.8 | 5.9 | 6.8 | 4.6 | 3.7 | 4.6 | 3.6 | 3.1 |
| Electricity price with capture (cents/kWH) | 7.1 | 8.2 | 5.1 | 7.6 | 9.4 | 10.1 | 6.1 | 9.4 | 5.4 | 4.4 |
| Cost of capture (\$/ton of carbon) | 77 | 117 | 66 | 106 | 158 | 264 | 121 | 227 | 195 | 132 |

studies used commercially available technology and estimated costs based on compressing the captured CO₂ to approximately 2000 psia for transportation. The table shows the estimated loss in energy, increase in the price of electricity, and cost associated with CO₂ capture from each plant type. The energy penalty from capture was least among the IGCC (9-23%) and NCGG (15-18%) plants as compared to the PC plant (23-34%). Consequently, the additional electricity costs from capture were highest among PC plants. The added electricity prices were between \$0.024-\$0.055/kWH for PC plants, while IGCC and NGCC prices were \$0.013-\$0.026/kWH and \$0.013-\$0.018/kWH higher, respectively. The overall cost of capture was slightly higher among PC plants (\$121-\$264/ton of carbon) than IGCC (\$66-\$158/ton of carbon) and NGCC (\$128-\$195/ton of carbon) plants.

Table 3.2 illustrates the additional costs associated with capturing CO₂ in the various power generating processes. However, to assess the cost-effectiveness of CO₂ capture, it may be more useful to compare its costs with other CO₂ mitigation strategies. Table 3.3 shows the range of net costs in constant 1990 dollars of the various CO₂ mitigation options. The CO₂ capture costs include the costs of storage or utilization. This data's uncertainty is demonstrated by the

Table 3.3. Potential and Cost of Various CO₂ Mitigation Options for the United States

| CO ₂ Mitigation Option | Reduction Potential (MMTC) | Net Cost (1990\$) \$/ton of carbon | |
|--|----------------------------|------------------------------------|------|
| | | High | Low |
| CO₂ Capture and Storage Technologies | | | |
| | | High | Low |
| Capture with utilization | 5.4 | 18 | 0 |
| Capture with EOR | 13.6 | 165 | 37 |
| Capture (ind. sources) with storage | 21.8 | 279 | 88 |
| Capture with geological storage | 245.2 | 334 | 114 |
| Capture with ocean storage | 163.5 | 334 | 114 |
| Energy Supply Technologies | | | |
| Nuclear | 408.7 | 224 | 48 |
| Hydroelectric | 8.2 | 139 | 92 |
| Biomass | 35.4 | 154 | 29 |
| Geothermal | 18.8 - 64 | 528 | 0 |
| Wind | 8.2 | 459 | 0 |
| Solar Photovoltaic | 109 | 1,468 | 84 |
| Solar Thermal | 147 | 653 | 88 |
| "Least Regrets or No Regrets" Options | | | |
| Energy efficiency | 115.8 - 170.3 | 22 | -308 |
| Supply efficiency | 27 | 7 | 0 |
| Fuel switching to gas | 231.6 | 169 | 62 |
| Forestation | 66 | 37 | 11 |

*source: (DOE, 1997)

wide range of cost estimates. Technological sinks appear relatively expensive compared to the various least regrets options. However, the costs of CO₂ capture and storage are very similar to nuclear and other renewable energy options.

The development of CO₂ capture technology is still in its infancy. There are many potential areas of research in capture technology that could lower the costs of these processes. For chemical and physical absorption, better understanding of the absorptive capacities and corrosion rates of solvents could yield lower costs. Also, the development of new solvents and system components may reduce the capital and energy costs for capture. Adsorbents that can operate at higher temperatures are already under consideration. Low-temperature or cryogenic processes may improve, as the development of efficient refrigeration cycles may enable competitive low-temperature distillation processes (DOE, 1999). Finally, there is further potential to lower costs of capture in the membrane processes. To date, research has only examined the composition of the membrane polymer to increase or decrease dissolution and diffusion rates. Further research into molecular modeling is needed to determine the full potential of membranes as a capture technology (DOE, 1999).

III. Storage

Once the CO₂ is captured, it must be used or stored securely for hundreds of years or longer. This stage of the process would be less expensive than the prior stage of capturing the CO₂ from the flue gas, ranging from \$15 to \$29/ton of carbon avoided, depending on local conditions and transportation costs (IEA, 1993). Storage capacities of very large quantities are needed because the atmospheric loading of carbon dioxide over the next 100 years could be as high as 408,719 MMTC (IPCC, 1996). Fossil fuel combustion alone results in worldwide emissions of about 1,635 MMTC per year (IEA, 1997).

There is substantial potential capacity for CO₂ storage in the ocean, aquifers, depleted oil and gas wells, and above ground in insulated tanks (see Table 3.4). In fact, all of these have the

Table 3.4 Global Utilization and Storage Capacity

| Option | Potential Global Storage (MMTC) |
|---------------------------|--|
| | |
| Utilization Method | |
| Enhanced Oil Recovery | 17,700 (109/yr) |
| Direct Biofixation | 41/yr |
| Chemicals | 24/yr |
| | |
| Storage Method | |
| Ocean Disposal | 380,000 - 5,400,000,000 |
| Aquifers | 23,700 - 735,700 |
| Exhausted Gas Wells | 38,000 - 84,500 |
| Exhausted Oil Wells | 10,900 - 51,770 |

potential sink capacity of sequestering thousands or even millions of MMTC (Table 3.4). There are also several utilization methods, including enhanced oil recovery (EOR), direct and indirect biofixation, and chemical use that can sequester smaller amounts of carbon. Table 3.4 does not present an exhaustive list of storage or utilization options, but it does contain the options most frequently discussed in current literature. While the wide range of potential storage capacities represents the uncertainty involved with these estimates, it is clear that they may more than sufficient.

Ocean Disposal -- The oceans are the ultimate natural sink and have the greatest long-term potential for carbon sequestration; indeed, they have the capacity to store all the CO₂ produced from fossil fuel combustion (Riemer et al, 1995). The oceans reach about 4000m deep and already contain near 10,900,000 MMTC, compared to only 204,359 MMTC in the atmosphere and 599,455 MMTC in the terrestrial biosphere (IPCC, 1996). The amount of carbon that would double atmospheric concentrations would change the deep ocean concentration by less than 2%. Currently, the oceans sequester about one-third of our anthropogenic CO₂ emissions, and over the next 1000 years almost 90% of today's anthropogenic CO₂ will be indirectly transferred to the oceans (DOE, 1999). Ocean disposal of captured CO₂ would speed this process to reduce CO₂ in the atmosphere.

The technology currently exists to directly inject CO₂ into the ocean. For the near future, a consensus is developing that the best strategy is to discharge the CO₂ at depths of 1000-1500m (Herzog, 1998). The deeper the CO₂ is injected, the more effectively it is sequestered. Two injection methods have been suggested to implement this strategy. One method would transport liquid CO₂ by tanker and discharge it from a pipe towed by a moving ship. The other would transport liquid CO₂ from shore and discharge it from the ocean bottom, which would form a rising droplet. Other approaches to injecting CO₂ into the ocean involve dry ice released from a ship at the ocean surface and CO₂-seawater mixture created at a depth of about 500 - 1000m. However, both approaches are probably not practical, since dry ice is very expensive and the CO₂-seawater mixture has a potential for environmental problems.

One major concern with ocean storage is the safety of the CO₂ once injected. In 1986, Lake Nyos in Cameroon released a large cloud of carbon dioxide that asphyxiated approximately 1500 people. Scientists believe the "bubble" was caused by a buildup of carbon dioxide in the deep waters. This has provoked concern for the security of CO₂ in the ocean, considering the large amounts that would be injected. While this concern deserves attention and further research, the chance of this type of occurrence appears much less likely in oceans. Water circulation in oceans is different from that of lakes. Due to continents being widely dispersed and ice caps at the poles, modern oceans appear to be well-mixed, which keeps carbon dioxide from building up in deep waters.

Terrestrial Disposal -- There are a number of ways in which carbon dioxide might be sequestered for long periods in the land base of the earth. Geologic formations, including aquifers and depleted oil and gas wells, are likely to provide the first large-scale sequestration of CO₂.

Aquifers -- Aquifers are probably the best long-term underground storage option because of their large potential capacity (Table 3.4). In aquifer disposal, carbon dioxide is injected into the aquifer, which displaces some water and causes some of the CO₂ to dissolve and some to remain as pure CO₂. The estimated storage for the United States could be very large, ranging from 1,362-136,239 MMTC (DOE, 1997). To put this capacity in perspective, the total annual U.S. power plant emissions are about 463 MMTC (DOE, 1997).

Two aquifer carbon sequestration projects may offer insight on the technological feasibility of the CO₂ storage process. Statoil has a project at Sleipner West off the Norwegian coast. Natural gas from this field contains about 10% CO₂ (DOE, 1999). Most of this CO₂ must be removed, therefore Statoil uses a solvent to absorb the CO₂ and then injects it into an aquifer about 1000m below the North Sea (DOE, 1999). This process involves the sequestration of about 1 million tons annually and is expected to store about 20 million tons over the project's lifetime.

Exxon and Pertamina are planning a project in the Natuna gas field below the South China Sea floor. In this field, natural gas contains over 70% CO₂, which must be separated before the natural gas can be sold. Exxon and Pertamina plan to inject the captured CO₂ into a deep aquifer below the South China Sea floor. Over a thirty-year period, the stored carbon dioxide from this project will correspond to the amount emitted from continuous production of 38,000 MW of electricity (DOE, 1997) - enough electric power to serve about four thousand U.S. households.

Exhausted Oil and Gas Wells -- Exhausted oil and gas reservoirs may be the most promising near-term geological storage option. This process works by injecting CO₂ into oil and gas reservoirs beneath an impermeable overlying lateral seal. Current depleted oil and gas reservoirs in the United States could contain about 2.9 billion tons of CO₂, and the potential reserves could hold close to 100 billion tons of CO₂ (DOE, 1997). These are promising targets for CO₂ storage because of the security issue. If the oil and gas that originally accumulated in the reservoirs didn't escape, then neither should the CO₂. This storage option may have the least unknown environmental consequences associated with it. Also, the availability of data, computer models, and general industry experience in the oil and gas industries will likely lower the cost of such CO₂ sequestration projects (DOE, 1999).

Enhanced Oil Recovery (EOR) -- Another option for sequestration are depleted but still active fields where oil recovery could be improved by the injection of CO₂. Enhanced oil recovery (EOR) would have the advantage of being commercially active at this time, as over 80% of commercially used CO₂ is for EOR (DOE, 1999). Beginning in Texas in 1972, CO₂ has been injected to improve oil production for years. The injected CO₂ works to improve oil production by two major mechanisms. First, it works to displace the oil, which is then pumped away. The injected CO₂ also dissolves in the oil, which causes the oil to be less viscous and flow more easily (DOE, 1999).

While this method does have the advantage of industry experience, it also has limitations. The amount of CO₂ that can be utilized for EOR and related applications is small compared to total CO₂ emissions, and CO₂ can currently be supplied from natural sources at about one-third the cost projected for CO₂ captured from power plants (Herzog et al, 1993). Consequently, there

is no real incentive to use captured power plant CO₂. Presently with oil prices of about \$100/t (\$13/bbl), captured CO₂ would have to cost less than \$25/t for the most efficient EOR applications to be economic (Riemer et al, 1995). Overall, the amount sequestered from EOR may not be large, but valuable operational experience can be gained that would benefit geologic sequestration in other types of formations (DOE, 1999).

Enhanced Coalbed Methane Production -- Coal formations could sequester CO₂ while also enhancing the production of natural gas. Injecting CO₂ into coal formations causes the adsorption of CO₂, which leads to the desorption of methane, improving natural gas production. The estimated sequestration potential from this option is fairly large, around 2724 MMTC in the United States alone.

The coal bed conditions, however, must be favorable for the application of CO₂ enhanced methane production to be safe and economical. For success, projects need favorable geology with sufficient permeability, cheap CO₂ availability, and adequate gas demand (DOE, 1999).

Currently, a couple of projects are testing this method for enhancing coal-methane production. Since 1996, operator Burlington Resources has sequestered over 57 million meters of CO₂ in coal seams at their Allison Unit in the San Juan basin in New Mexico and Colorado. Initial results show that the methane recovery is improved with CO₂ injection and that it may be profitable (IEA, 1998). Another pilot demonstration is taking place in Alberta, Canada. A technical assessment later this year should provide details into the success of the project.

Chemicals -- Replacement of CO₂ that is currently produced for the chemical industry with captured flue gas CO₂ is a utilization option. This option requires careful consideration because the original source of CO₂ could be a by-product and may be vented to the atmosphere (Riemer et al, 1995). Currently, the food and drink industries, refrigeration, and inerting applications are the greatest users of CO₂. Researchers have noted that there is potential to substitute currently used CO₂ with recycled CO₂ and thereby expand the use of CO₂.

A leading candidate for expansion, Dimethylcarbonate (DMC), which can be produced from CO₂, has an estimated market potential of 0.54 MMTC/year and offers the environmental benefit of replacing phosgene (IEA, 1995). The industrial sector could find opportunities where pure CO₂ is produced and could be reused or used as feedstock in other processes, such as in ethylene and ammonia production.

However, while expansion of recycled CO₂ is possible in these industries, it can only make a very small contribution to the mitigation of CO₂ emissions. For example, in a vigorous (U.S.) CO₂ mitigation effort, many small industrial activities could be converted to power plant CO₂ feedstreams, but the potential impact would be much less than 1% of the total power plant CO₂ generated (DOE, 1997).

Direct Biofixation -- Direct biofixation involves artificially increasing the growth of aquatic plants to increase the transfer of CO₂ across the water surface. This process could be accomplished through localized fertilization with iron, or by large-scale fertilization with nitrogen. Research shows that this process is possible, as iron fertilization in high-nutrient, low-

chlorophyll waters have demonstrated that growth in phytoplankton is feasible (Coale et al, 1996). Some companies such as Ocean Farming, Inc., are trying ocean fertilization to enhance their fish harvest and claiming carbon sequestration as a secondary benefit.

While these utilization and storage options do appear to be low-cost and have an enormous amount of storage capacity, several environmental and technological questions could be limiting factors.

Storage Limitations -- Environmental and technical uncertainties represent the greatest impediments to CO₂ storage. Environmental impacts near the CO₂ injection point and long-term impacts on the ocean ecosystem must be better understood. The injected CO₂ will likely lower pH because of reactions with the seawater. This may have negative impacts on various marine organisms. Those most likely affected will be non-swimming marine organisms near the injection level (1000 - 1500m). The microbial community may also experience unknown impacts on biogeochemical processes (DOE, 1999). Clearly, substantial research is still needed in the area of ocean storage.

Sequestration effectiveness (security) also needs to be better understood. It is critical that we know the tradeoffs involved (retention time, environmental impacts) with injecting the CO₂ at various depths. Only with this information will it be possible to find the optimal injection strategy.

Further research is still needed into the ecological consequences of the other ocean-related sink, large-scale algae fertilization. Imperative is the ability to predict how ecosystems will react and change to sustained fertilization. Further research is also needed into the effectiveness of ocean fertilization. We must know the amount of carbon transported from the ocean's surface to the deep ocean and what happens to the carbon after it reaches the deep ocean (DOE, 1999).

There are also unresolved issues associated with aquifer CO₂ storage. When the CO₂ is injected, the water is likely to remain in the formation, which increases the formation pressure over a large area. This could translate into land surface deformations and induce seismicity. Further research is needed to determine the likely amount of CO₂ leakage over time from these aqueous formations. While some leakage may be beneficial, its consequences need to be understood.

Overall, the relatively high cost of capture technologies and unknown impacts from storing or using the CO₂ will need to be addressed before widespread implementation of technological sinks can occur. However, technological sinks have some possibilities for application in the short term and a great deal of potential for the longer term.

IV. Research and Development

Without any type of government action, there will likely be little technological sink application in the next 10 years. In the longer term, there is substantial opportunity for the application of CO₂ capture and disposal, as more research finds ways to reduce the cost. Also, since capture technology can be used to retrofit existing power plants, this may start to occur in

various plants, especially those that have good alternatives for CO₂ disposal. Given the likely importance of atmospheric CO₂ levels in the future, it is possible that new plants will be designed to take advantage of CO₂ capture and storage technology. Most new power plants could be developed to include CO₂ capture technology, similar to plant designs today that include SO₂, NO_x, and particulate controls. These new plants could also be located with CO₂ sequestration as a concern, therefore allowing easier CO₂ disposal.

The U.S. research effort into technological sinks has been minimal, allocating less than \$10 million on CO₂ capture and storage since 1989. In fact, current spending on CO₂ capture and storage is at about \$1-\$2 million per year. This amount is extremely small compared to the \$1.7 billion annually spent on climate change research. In fact, less than one percent of spending on climate change research goes toward research on technological sinks. When compared to the overall U.S. climate change budget of about \$5 billion per year, CO₂ capture and storage spending is less than half a percent.

While the United States has not yet put forth much effort into this area of research and development, other countries, especially Japan, have started to show considerable interest. The Japanese have undertaken the largest research program in the world on CO₂ capture and storage, currently spending over \$350 million per year. The primary focus of their research has been CO₂ fixation and utilization. One major project involved research into fixation by algae, while another project examined catalytic hydrogenation of CO₂, including research on CO₂ capture through membranes. Spending on each project was \$123 million and \$77 million, respectively. Overall, the Japanese research program into CO₂ fixation and utilization involves a wide variety of programs ranging from CO₂ capture modification and development to geological storage and utilization (DOE, 1997).

Japan has also recently initiated another major project examining aspects of ocean disposal (DOE, 1997). The project includes research activities on the behavior of liquid CO₂ released into the ocean, various engineering systems for CO₂ injection, security of the CO₂, and its long-term environmental impact. These possibilities are of particular interest to Japan, given its proximity to the ocean and limited geological storage capacity (DOE, 1999).

Need for Further Research -- Further research into CO₂ capture and storage technology is essential and should be increased. The U.S. Department of Energy (DOE) appears to agree, stating that “the existing R&D program should be expanded soon.” In fact, the DOE just released a 200-page working paper on carbon sequestration and science. The paper highlighted many areas for further research and appeared optimistic that future research could provide substantial improvements in this technology. “The carbon sequestration options include topics that are inadequately investigated compared with many other energy areas, making the opportunities for significant breakthroughs high” (DOE, 1999).

To combat climate change in the long-term, more costly strategies that involve further emissions reductions such as nuclear energy, renewable energy, and CO₂ capture and storage will need to be considered. The extensive implementation of each of these strategies does have problems. Nuclear energy will have to resolve the issues of safe waste storage and public acceptance. Renewables have high costs, problems with storing energy, and limited applicability. Technological sinks need to reduce the costs of capture and prove that storage is

both secure and environmentally safe. While there has been considerable research into nuclear and renewable energy, research into CO₂ capture and storage is still in its infancy. In fact, billions of DOE research dollars have been spent on the development of the alternative longer-term mitigation strategies of increased nuclear and renewable energy, while research efforts into CO₂ capture and disposal have been minimal (DOE, 1997). Consequently, there is potential to reduce costs and demonstrate environmental safety and security in storage with further research.

As this technology becomes more cost-effective in the future, the optimal tool to encourage its implementation may be a CO₂ trading program, similar to the SO₂ program for power generation plants. CO₂ emissions could be capped at a certain level, while allowing the power plants flexibility in meeting these allowances at minimum costs, likely through some integration of CO₂ capture and storage. Additional allowances among the power plants could be traded or banked, while failed compliance would result in fines. The success of the SO₂ program with savings of an estimated \$4 billion per year indicate that a similar program for CO₂ would likely achieve emissions reductions at a minimum cost. A CO₂ trading program could also provide a direct incentive for increased research and development in the area of technological sinks. This would likely stimulate U.S. private sector research and development in this area, which has been nonexistent to date.

V. Conclusion

While the timing and magnitude is debatable, scientific evidence strongly indicates that CO₂ emission controls will be needed eventually. Since one set of options will not solve the climate change problem, it seems logical to research all potential mitigation strategies so that a range of options will be available in the future. Yet U.S. research efforts have largely ignored technological sinks. Therefore, this chapter proposes a six-year increased technological sink research program with the following strategies and goals:

Decrease capture cost. Currently, the greatest limitation to capture implementation is its high cost. With further research, these costs will likely decrease. Research should focus on chemical absorption and membranes, due to their large potential for reduced costs.

Increase understanding of storage feasibility. The greatest concerns regarding storage options involve their unknown ecological consequences and technical feasibility. Further research into all storage options should reduce these uncertainties.

Encourage private investment. Leading research in many fields is often accomplished in the private sector. Collaborative pilot projects with various industries (utilities, oil and gas companies, etc.) should be developed. Joint Implementation possibilities for capture and storage should also be promoted.

Make the United States the world leader. At its current pace, Japan will become the dominant world leader in CO₂ capture and sequestration. An increased research budget should allow the United States to compete for leadership in this area. Technological leadership could prove beneficial, as these technologies could prove to be valuable exports in the future.

To achieve these strategies and goals, a budget averaging \$60 million per year for 6 years is recommended as described below in Table 3.5:

Table 3.5. Budget Recommendation

| Fiscal Year | Collaborative Projects (millions) | Capture (millions) | Storage (millions) | Total (millions) |
|-------------|-----------------------------------|--------------------|--------------------|------------------|
| 2000 | \$25 | \$10 | \$5 | \$40 |
| 2001 | \$25 | \$10 | \$5 | \$40 |
| 2002 | \$35 | \$15 | \$10 | \$60 |
| 2003 | \$35 | \$15 | \$10 | \$60 |
| 2004 | \$50 | \$20 | \$10 | \$80 |
| 2005 | \$50 | \$20 | \$10 | \$80 |

While there is undoubtedly overlap between these categories of research spending, the distinction is useful as a reflection of priority. Collaborative projects receive a large portion of the budget for several reasons. First, these projects could stimulate private sector involvement, allowing pilot projects, such as the aquifer storage project off the coast of Norway, to develop quickly. Collaborative projects would also entail substantive work with the Norwegians, Japanese, and other technological sink researchers. These projects would also provide extensive knowledge on the application of capture and storage technology. Furthermore, collaborative projects could involve joint implementation pilot projects, which if successful, may be counted toward early action.

Finally, private sector involvement could also assure the longevity of technological sink research and relieve budgetary pressures from the federal government. More funding is allocated toward capture research than storage because the present high costs associated with capture are the biggest obstacle to overcome before widespread CO₂ capture and storage implementation would be possible. Given this increased funding and research plan, the goal of U.S. leadership in technological sinks should be attainable.

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